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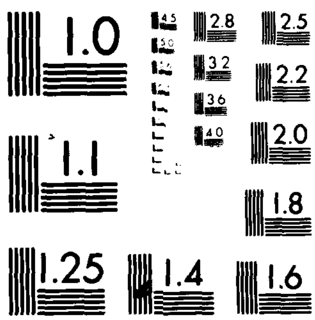

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TECHNICAL REPORT (12) TR-276

CATENARY ANALYSIS FOR MAVA BUOY ARRAY RECOVERY

CARLOS R. MAYORAL

January 1982

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FOREWORD

The effort described in this report was an integral part of the MAVA buoy array recovery performed by the Engineering Department, Naval Oceanographic Office (NAVOCEANO). The recovery, in support of the Acoustics effort of NAVOCEANO, demonstrated the successful application of the theoretical computations presented herein. If further information or discussion on this topic is desired by the reader, contact Commanding Officer, Naval Oceanographic Office, Attention Mr. Carlos R. Mayoral, Code 6320, NSTL Station, Bay St. Louis, MS 39522, 601-688-4344 (FTS 494-4344, AV 485-4344).

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TR-276	2. GOVT ACCESSION NO. AD-A	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CATENARY ANALYSIS FOR MAVA BUOY ARRAY RECOVERY		5. TYPE OF REPORT & PERIOD COVERED Final 11/80 - 12/80
		6. PERFORMING ORG. REPORT NUMBER TR 6300-2-81
7. AUTHOR(s) CARLOS R. MAYORAL		8. CONTRACT OR GRANT NUMBER(s) N/A
9. PERFORMING ORGANIZATION NAME AND ADDRESS Maintenance Engineering Division Naval Oceanographic Office NSTL Station, Bay St. Louis, MS 39522		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Acoustics
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Oceanography Command NSTL Station, Bay St. Louis, MS. 39529		12. REPORT DATE January, 1982
		13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) See #11		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

N/A

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Catenary analysis; MAVA buoy recovery; Deep ocean sensor recovery.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A two-dimensional static catenary analysis technique developed for recovery of a MAVA buoy array deployed at a depth of 4515 m. is described. Unique requirements for recovery, including the need to retrieve the anchor releases as well as the buoy, led to the use of an unusual array geometry. Values calculated from the analysis provided an accurate indication of the array geometry and were essential in the highly successful recovery.

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S/N 0102-LF-014-6601

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INTRODUCTION

In August 1980, a NAVOCEANO MAVA[1] array was deployed in the Atlantic at a depth of 4515 m. Attempts to retrieve the array were unsuccessful. The Engineering Department at NAVOCEANO was requested to provide expertise in the development of a method for recovering the array.

The MAVA array (figure 1) was a taut wire vertical mooring held up by a syntactic foam instrumented buoy and stationed by a concrete anchor. The array consisted of:

a. an instrumented buoy located at 1917m depth,

b. 1495m of one-inch electro mechanical Kevlar cable with 12 ITC hydrophones mounted in-line,

c. 24 football floats distributed along the cable,

d. 1000m of 3/8 in. Kevlar mooring line,

e. dual acoustic releases mounted approximately 100m above the bottom,

f. 100m of 1/4 in. wire-rope mooring cable, and

g. 4000 lb. (in air) concrete anchor at 4515m depth.

Initial attempts at retrieval during the recovery cruise, by activation of the two AMF releases, failed. One release would not respond to acoustic interrogations. The second would respond to all interrogation modes but would not release.

An attempt at retrieval was also made by dragging a 300 lb. grappling hook in a small circle around the array. Three separate drag attempts were made without success. No further recovery attempts were made during the recovery cruise.

Initial research by the Engineering Department determined that no tried and proven method for deep ocean recovery of a moored array was available. It was determined that several methods were potentially capable of success. Particularly promising techniques were: using a cutting line in a fashion similar to the methods used in mine sweeping; or using grapples which would hook the array for retrieval or which would cut the array so the MAVA buoy would be free to surface.

In synthesizing the actual technique to be used, an additional requirement was decided upon. It was hoped that not only would the buoy itself be recovered but that also the failed anchor releases would be retrieved. This would allow acoustic tracking of the MAVA buoy during recovery using the anchor releases. It was also desireable to retrieve the anchor releases so that determination of the cause for failure could be made. This meant recovering the entire array or severing the array at a point below the releases which were located 100 meters from the bottom.

[1] Moored Acoustic Vertical Array

The recovery method developed involved a combination of all the techniques mentioned: a cutting line and grapples with sharpened edges which would either hook the array for retrieval or cut the mooring line. In order to provide position information two transponders and a pinger were mounted on the cutting line and cable. Furthermore, in order to provide the necessary control for height and sweep of the cutting line and grapples, an anchor, depressor weight and sentinel weight were to be used. The configuration of the recovery array is depicted in figure 2.

It was concluded that the exact position and geometry of the recovery array at all times during the operation would be crucial. In order to realize this capability the operation would have to be carried out as a quasi-static process in which the recovery array velocities through the water were minimized. This would permit two-dimensional static catenary analysis of the array geometry rather than a less precise and far more difficult three-dimensional dynamic analysis.

The catenary analysis used in the development and execution of the recovery procedure is the subject of this report. The analysis follows standard static catenary analysis techniques with simple modifications tailored to the recovery array design used.

CATENARY ANALYSIS

The geometry assumed by the sweepline and cable with fixed anchor and sentinel weight formed two distinct catenaries joined at the sentinel. This geometry is illustrated in figure 3. The anchor and depressor weight are at point A with the sentinel weight at point B. The arclength $\overline{AB}$ is the sweepline which forms one catenary while the rest of the cable, arclength $\overline{BC}$, forms the other.

In order to set up the catenary analysis, it was first necessary to decide what parameters were known or could be determined by direct measurements and what variables would have to be calculated from the analysis. Tables of fixed constants, measured parameters and calculated variables were set up. The nomenclature for these values are given in Tables 1, 2 and 3.

Table 1 cites the "Fixed Parameters". These values would not change during the retrieval operation, but were input values that could be changed at any time up until the actual operation commenced. The linear density of the cable would not change unless a different cable was used. The depth of the MAVA array, given to be 4515 meters, was a value that could be updated upon arrival at the operational area. The depressor and sentinel weights were approximate values that would be refined when the weights were actually constructed, and the length of the sweepline would be fixed at the time the retrieval array was deployed.

Table 2 lists those parameters that could be measured during the operation. For the catenary calculations these values are redundant and some could serve as inputs for the calculations while the rest provide a means for checking the accuracy of the theoretically computed values. Furthermore, any of these values could be computed using the catenary equations from the other inputs. If any of the instrumentation failed the analysis provided a means for calculating the missing parameter.

Table 3 lists some calculated values used in determining the sweepline and cable geometry. This information would be used to ensure that the sweepline was off the bottom and simultaneously below the MAVA array releases.

Although calculators were programmed to perform the calculations during the operation, it was anticipated that it would be more convenient to have lookup tables ready with plots depicting the anticipated cable configurations. This allowed a visual indication of the cable geometry and would help reduce the amount of calculating that would have to be done during the retrieval operation.

CATENARY CALCULATIONS

Usual catenary calculations employ a coordinate system whose origin is offset some vertical distance from the lowest point of the catenary (i.e., where the catenary becomes horizontal). This is demonstrated in figure 4 where the offset is c. H is the horizontal tension at the bottom and T is the tension at the top of the catenary. The arclength is s and W is the weight of the cable occurring at the midpoint of the arc.

It could not be assumed that the sweepline would form the geometry depicted in figure 4. If too much cable were payed out, then some of the line would lay on the bottom. This would have the effect of moving point A farther down the cable, resulting in a new catenary of shorter arclength. In this case the standard catenary equations would still hold and only an adjustment to the position of the new point A and coordinate system need be made. On the other hand, if not enough cable were payed out to achieve the geometry shown, then the assumption that the cable was horizontal at point A would be incorrect.

This led to two cases for consideration:

Case 1 - sweepline catenary is horizontal at point A

Case 2 - sweepline catenary is not horizontal at point A

The first case led to straightforward calculations using standard catenary equations. The second case required some additional analysis and introduced new parameters for consideration. Both cases will be considered separately.

CATENARY ANALYSIS FOR CASE 1

Figure 4 can be considered a free-body diagram of the sweepline anchored at point A without the sentinel weight. The vertical coordinate offset c is calculated from:

$$c = \frac{s^2 - d^2}{2d} \qquad (1)$$

where: s = catenary segment arclength
d = height of point B off bottom

The arclength s would be fixed when the array was assembled. The height d would be measured during the operation using the acoustic pinger attached to the cable. For a given arclength and height the horizontal length x of the cable is:

$$x = c \ln \left(\frac{y}{c} + \sqrt{\left(\frac{y}{c}\right)^2 - 1} \right) \qquad (2)$$

where: $y = c + d$

The horizontal distance x between the anchor and sentinel was to be measured using acoustic releases attached to the array as transponders. This value was, therefore, an input to the calculations. However, should either of these releases fail to transpond the parameter could be calculated using equation (2). Furthermore, the measured value could be used as a check of the analysis by comparing with the calculated value.

The tension at the bottom of the catenary is given by:

$$H = cw \qquad (3)$$

where: w = linear density of cable

The tension at the top of the catenary is:

$$T = yw \qquad (4)$$

The weight of the catenary is the linear density times the length:

$$W = sw \qquad (5)$$

Summing forces in the x and y directions and dividing yields the angle the tension at point B makes with the horizontal:

$$\theta = \tan^{-1} \left(\frac{W}{H}\right) \qquad (6)$$

A free-body diagram of point B where the sentinel weight attaches to the two cable segments is depicted in figure 5. In this figure P represents the sentinel weight, T and θ represent the tension and its direction in the lower catenary cable segment, and T' and ϕ represent the tension and its direction in the upper catenary cable segment. Summation of forces in equilibrium yields:

$$\phi = \tan^{-1} \left(\frac{T\sin\theta + P}{T\cos\theta}\right) \qquad (7)$$

and

$$T' = \left(\frac{T\sin\theta + P}{T\cos\theta}\right) \qquad (8)$$

The cable segment $\overline{BC}$ forms a portion of a catenary whose loading conditions are calculated for point B. In order to use standard catenary analysis, the segment can be extended to include an imaginary portion of cable which would form a single continuous catenary with the same resultant loads at point B. This concept is illustrated in figure 6.

The segment $\overline{A'B}$ is the imaginary portion with arclength s', horizontal length x' and horizontal tension H'. The vertical displacement for the catenary coordinate system is c'. Figure 7 depicts a free-body diagram of this segment. The parameters in this figure are calculated as follows. The value of y' is:

$$y' = \frac{T'}{w} \tag{9}$$

The horizontal tension H' is:

$$H' = T'\cos\phi \tag{10}$$

The coordinate displacement c' is:

$$c' = \frac{H'}{w} \tag{11}$$

The height d' is given by:

$$d' = y' - c' \tag{12}$$

The horizontal distance is then:

$$x' = c' \ln\left(\frac{y'}{c'} + \sqrt{\left(\frac{y'}{c'}\right)^2 - 1}\right) \tag{13}$$

The arclength s' is:

$$s' = \sqrt{y'^2 - c'^2} \tag{14}$$

The weight of the imaginary segment is:

$$W' = s'w \tag{15}$$

For the entire catenary $\overline{A'C}$ in figure 6 we have:

$$D' = D + d' - d \qquad (16)$$

and

$$Y' = D' + c' \qquad (17)$$

The horizontal distance is:

$$X' = c' \ln \left(\frac{Y'}{c'} + \sqrt{\left(\frac{Y'}{c'}\right)^2 - 1} \right) \qquad (18)$$

The arclength S' is:

$$S' = \sqrt{Y'^2 - c'^2} \qquad (19)$$

Equations (9) through (15) provide the parameters for the imaginary catenary segment $\overline{A'B}$, while equations (16) through (19) give the required parameters for the entire (imaginary and actual segments) catenary $\overline{A'C}$. It is now a simple matter of subtracting the imaginary segment from the entire catenary, yielding the required parameters for segment $\overline{BC}$, the actual catenary segment.

The horizontal distance X for the catenary segment $\overline{BC}$ is:

$$X = X' - x' \qquad (20)$$

The tension in the cable at point C (which represents the ship) is:

$$T'' = Y'w \qquad (21)$$

The arclength S is:

$$S = S' - s' \qquad (22)$$

The total length of cable $\overline{ABC}$ shown in figure 1 is given by:

$$S_t = s + S \qquad (23)$$

The total weight of the cable plus load is:

$$W_t = S_t w + P \qquad (24)$$

The total horizontal distance X_t is:

$$X_t = X + x \qquad (25)$$

In summary, the known values are:

- w = linear density of cable
- s = length of sweepline
- d = height of sentinel
- P = weight of sentinel
- D = depth from surface to bottom

The calculated parameters, not including intermediate values, are:

- H = horizontal tension at anchor
- T = tension in sweepline at sentinel
- T' = tension in cable at sentinel
- T'' = tension in cable at ship
- x = horizontal distance of sweepline
- λ_t = horizontal distance from anchor to ship
- S_t = total cable payed out from anchor to ship

The calculated values are used to indicate the tensions in the cable and the geometry of the cable. As previously mentioned, the tension at the ship T'', and the distances x, X_T and S_T could be measured inputs. In fact, such measurements could serve as a means of verifying the theory and the calculations.

CATENARY ANALYSIS FOR CASE 2

We will next consider the case when the sweepline is not horizontal at the anchor. In this case, the sweepline segment forms a portion of a catenary. Development of the analysis can be made along the same lines used for the cable segment $\overline{BC}$ in Case 1; which is to assume the catenary segment to be extended so that the usual catenary calculations may be applied. This is illustrated in figure 8.

In this case the loading conditions are unknown. For a direct analysis of this situation, values for at least two parameters must be assumed. For our purposes, the values s, the segment arclength $\overline{A'B}$ and θ, the angle of the sweepline at the sentinel, were chosen. The analysis proceeds as follows.

Select s and θ. Known values are s_a, the actual length of the sweepline from anchor to sentinel, and w, the linear density of the cable. The horizontal tension at A', the bottom of the imaginary catenary segment, is calculated from equation (6) by:

$$H = \frac{W}{\tan\theta} \tag{26}$$

Where W is the weight of the total segment including the imaginary part and is calculated using equation (5). From equation (3) the coordinate system vertical displacement is:

$$c = \frac{H}{W} \quad (27)$$

Using equation (1) the vertical distance from A' to B is:

$$d = -c + \sqrt{c^2 + s^2} \quad (28)$$

The horizontal distance x is given by equation (2). The tension T at the top of the sweepline is calculated from equation (4).

Using equation (28) the vertical height of the imaginary segment $\overline{A'A}$ is:

$$d' = -c + \sqrt{c^2 + s'^2} \quad (29)$$

Where: $s' = s - s_a$

From equation (13) the horizontal length for the imaginary segment is:

$$x' = c \ln\left(\frac{y'}{c} + \sqrt{\left(\frac{y'}{c}\right)^2 - 1}\right) \quad (30)$$

Where: $y' = c + d'$

Therefore, the horizontal distance for the actual catenary segment $\overline{AB}$ is:

$$x_a = x - x' \quad (31)$$

The vertical height is:

$$d_a = d - d' \quad (32)$$

The tension at A, the anchor is:

$$t' = y'w \quad (33)$$

This tension occurs at an angle θ' given by equation (6) as:

$$\theta' = \tan^{-1} \frac{W}{H} \quad (34)$$

The tension at point A may be divided into horizontal and vertical components. The vertical component tends to lift the depressor weight decreasing the horizontal load that it can hold. The tension components are given by:

$$P_H = t' \cos\theta' \quad (35)$$

$$P_V = t' \sin\theta' \quad (36)$$

Equations (26) through (36) may be used to analyze the sweepline tensions and geometry. Equations (7) through (25) of Case 1 may be used to calculate the rest of the cable parameters (substituting x_a for x and d_a for d where required).

In summary, the following values are assumed:

s = length of lower catenary segment including imaginary portion and sweepline

θ = angle of sweepline at sentinel

The known values are:

s_a = length of sweepline

w = linear density of cable

P = weight of sentinel

D = depth from surface to bottom

The calculated values included:

P_H = horizontal tension load at anchor

P_V = vertical tension load at anchor

T = tension in sweepline at sentinel

x_a = horizontal distance of sweepline

d_a = height of sentinel

θ = angle of sweepline at anchor

T" = tension of cable at ship

X_T = total horizontal distance from anchor to ship

S_T = total line payed out from anchor to ship

Again, many of the calculated values could be measured directly with instrumentation. Tables were developed using values of s from 2200 ft. to 4000 ft. and θ varying from 5^o to 80^o (it was estimated that a sweepline length of approximately 2000 feet would be used). Plots were also made drawn to scale of the cable and sweepline at the various geometries. Figures 9 and 10 are examples of these plots. It was felt that from instrument readings "interpolation" of cable geometries between the various plots could be made. In this way, a visual indication of cable behavior could be made in real time, hopefully, without the need of simultaneous calculations.

Summary and Conclusions

The array analysis technique developed was based on standard two-dimensional static catenary analysis. Prior to the recovery operation tables and plots of various array geometries were prepared. These tables and most especially the plots were referred to throughout the recovery. They afforded a visual indication of the recovery array behavior. Comparison of calculated values with instrumentation measurements demonstrated excellent correspondence proving the analysis gave an accurate interpretation of the recovery array geometry. Redundancy between calculated and measured values also proved to be more than useful as early in the operation cable tension measurement was lost. Since cable tensions approached a critical load level, the calculated tension values had to be referred to throughout the recovery operation. Furthermore, intermittent loss of fathometer measurements had to be compensated by use of geometry calculations in order to maintain the required sweepline altitudes.

The success of the operation gives final credence to the accuracy and utility of the analysis techniques described. The MAVA array was severed below the acoustic releases and recovered as planned on the very first attempt.

TABLES

Table 1

Fixed Constants

w - linear density of 9/16 in. cable

D - ocean depth at MAVA array

s - length of sweepline

P - weight of sentinel

Table 2

Measurable and Calculatable Parameters

T"- tension of cable at ship

d - height of sentinel off bottom

x - horizontal distance between anchor and sentinel

X - horizontal distance between sentinel and ship

S - amount of cable payed out

Table 3

Calculated Parameters

H - horizontal tension at bottom of catenary

T - tension at top of sweepline

T'- tension at bottom of cable

W - weight of cable

θ - angle at top of sweepline

ϕ - angle at bottom of cable

P_H- horizontal component of cable tension at depressor

P_V- vertical component of cable tension at depressor

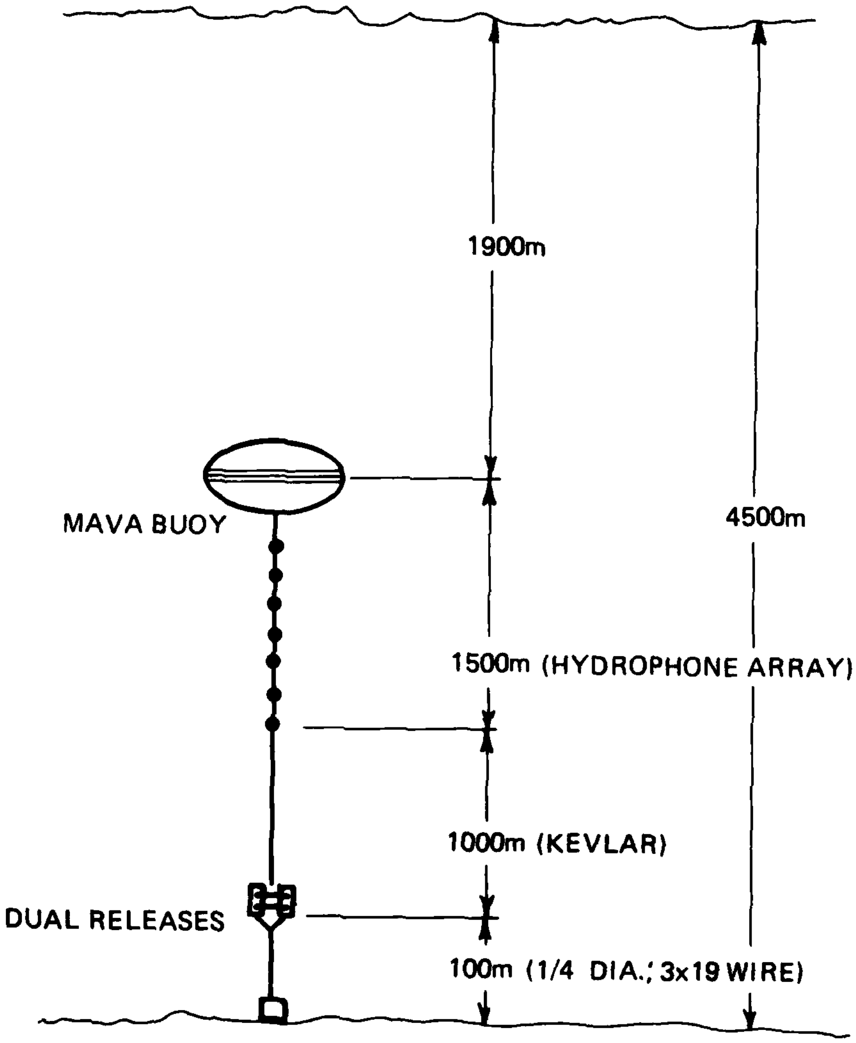

FIGURE 1 MAVA

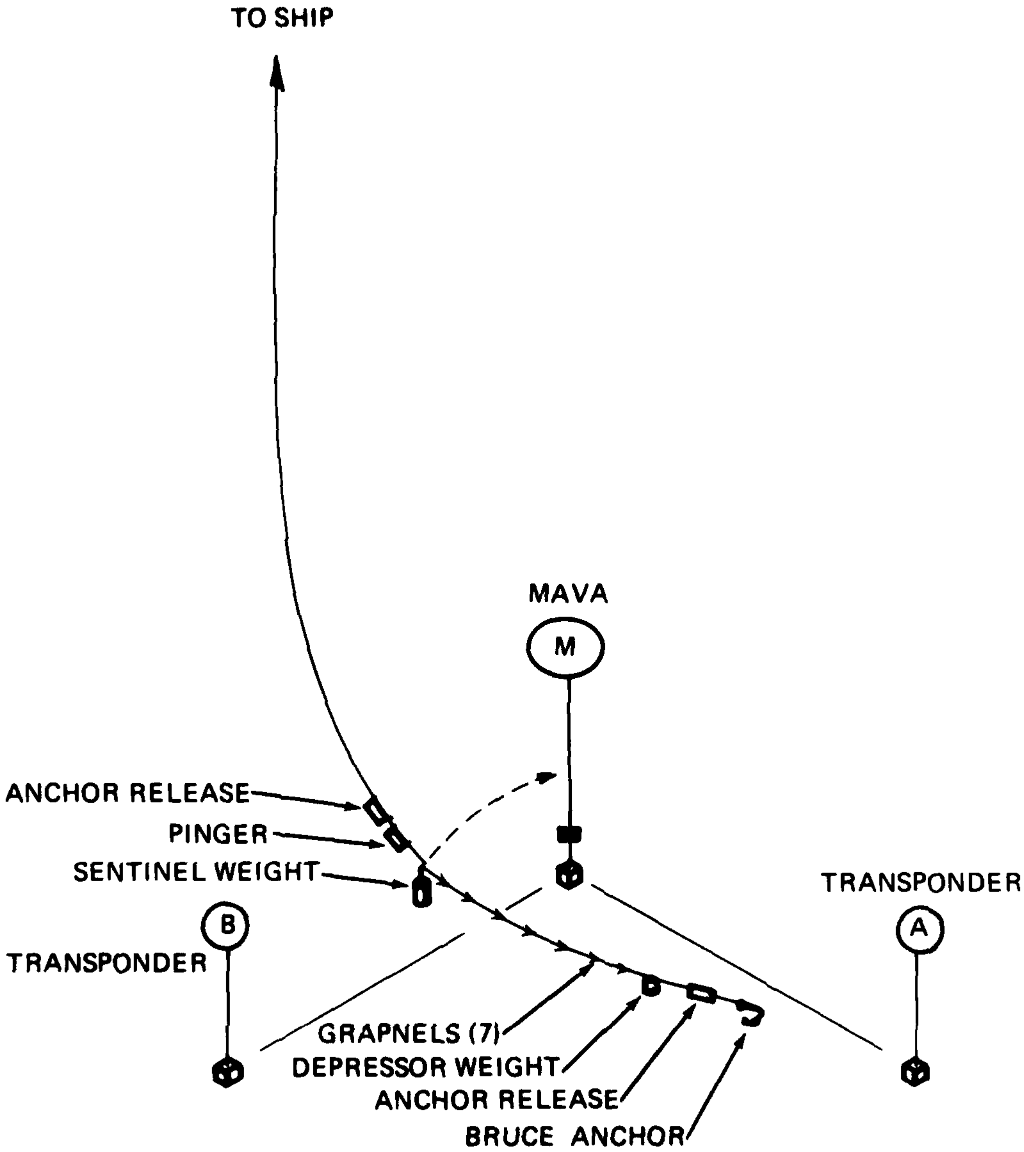

FIGURE 2 MOORED SWEEPLINE TECHNIQUE

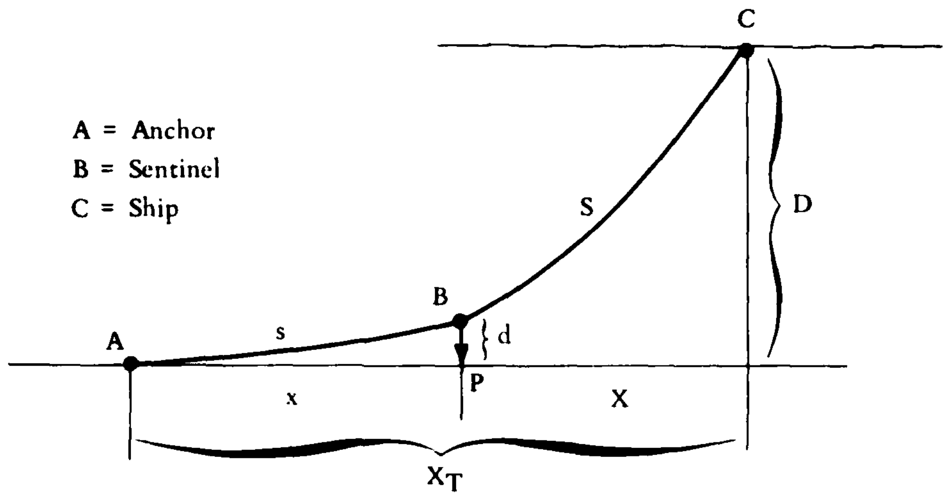

FIGURE 3 RECOVERY ARRAY GEOMETRY

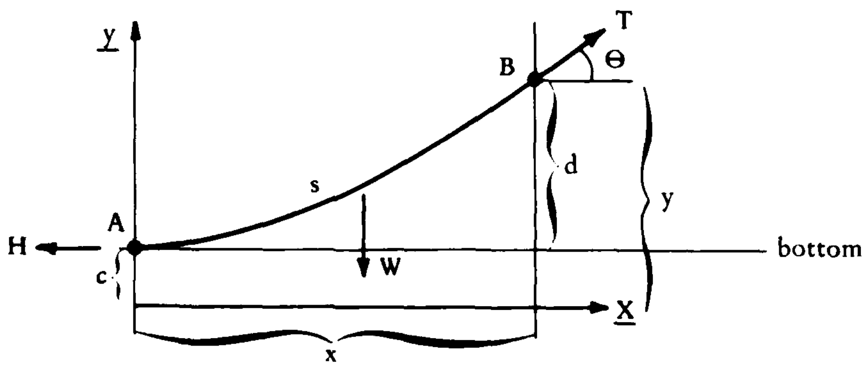

FIGURE 4 SWEEPLINE GEOMETRY

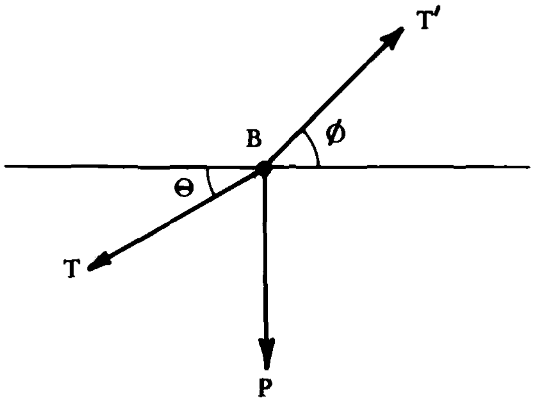

FIGURE 5 FREE BODY DIAGRAM AT SENTINEL

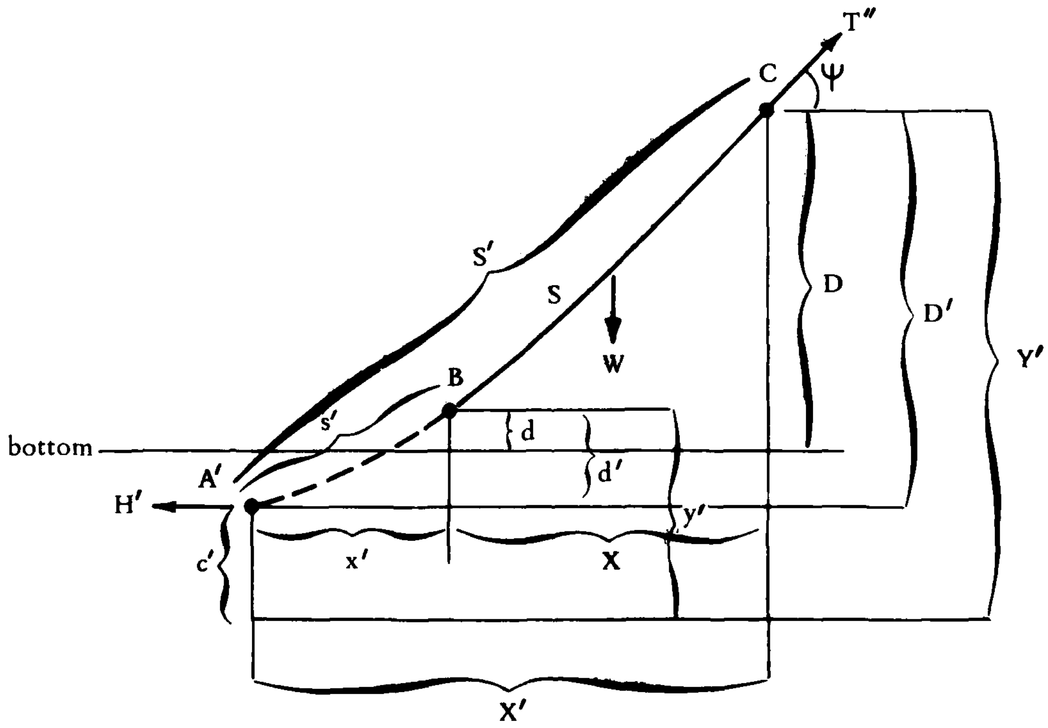

FIGURE 6 ARRAY GEOMETRY AND IMAGINARY SEGMENT

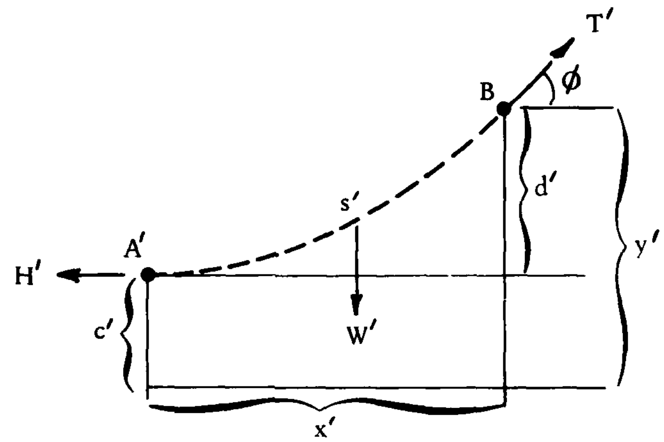

FIGURE 7 GEOMETRY OF IMAGINARY SEGMENT

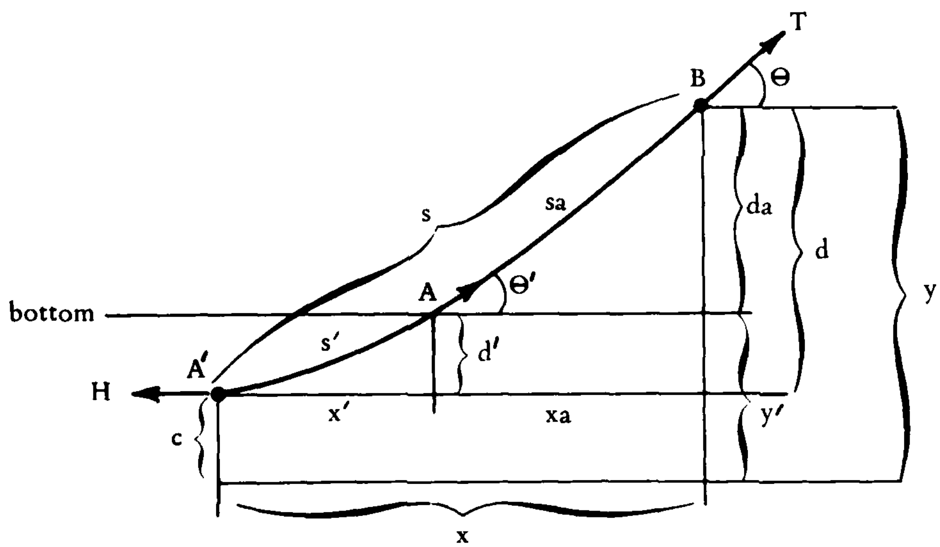

FIGURE 8 "EXTENDED" ARRAY GEOMETRY

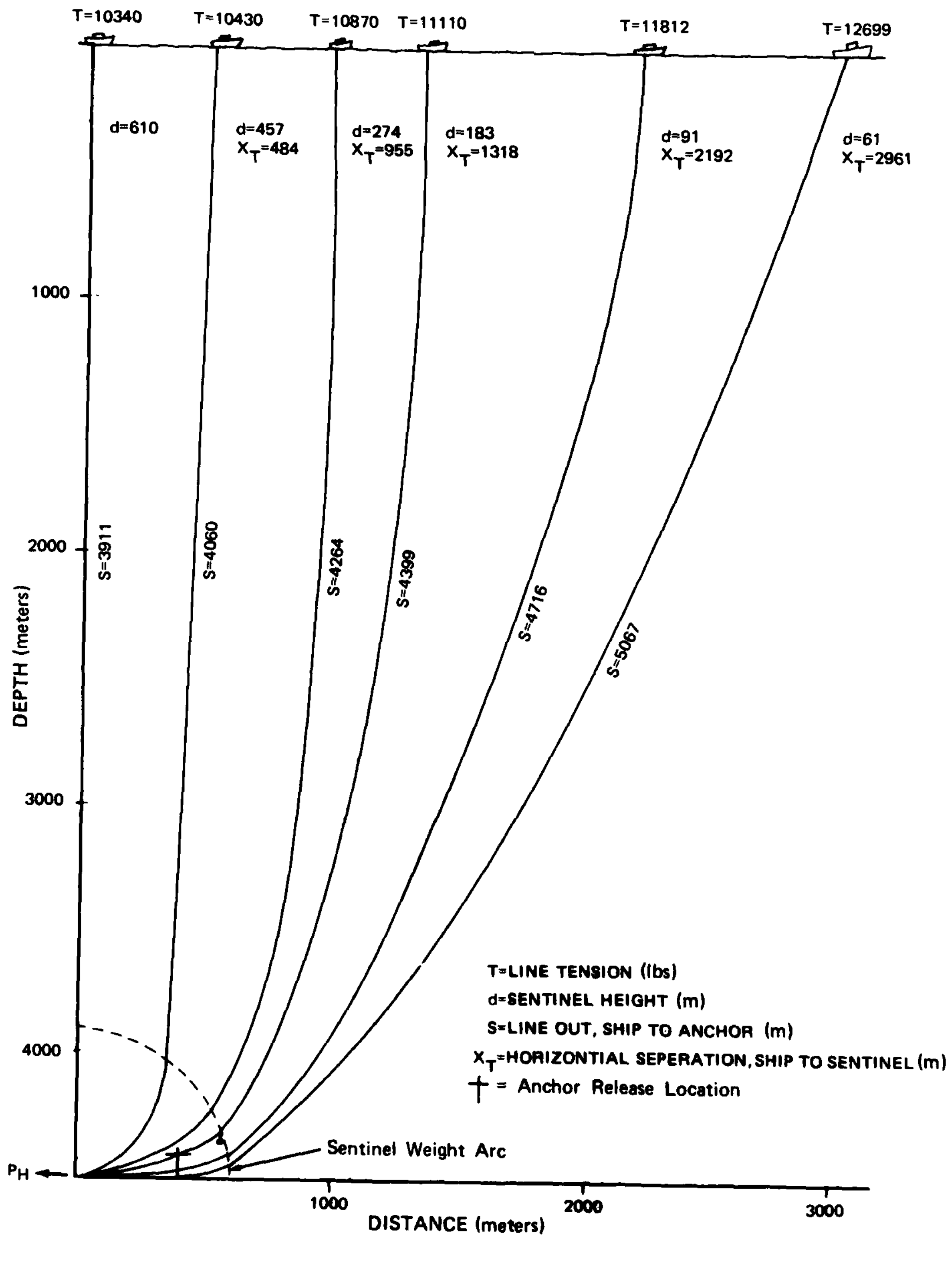

FIGURE 9 CATENARY DETAIL CASE 1

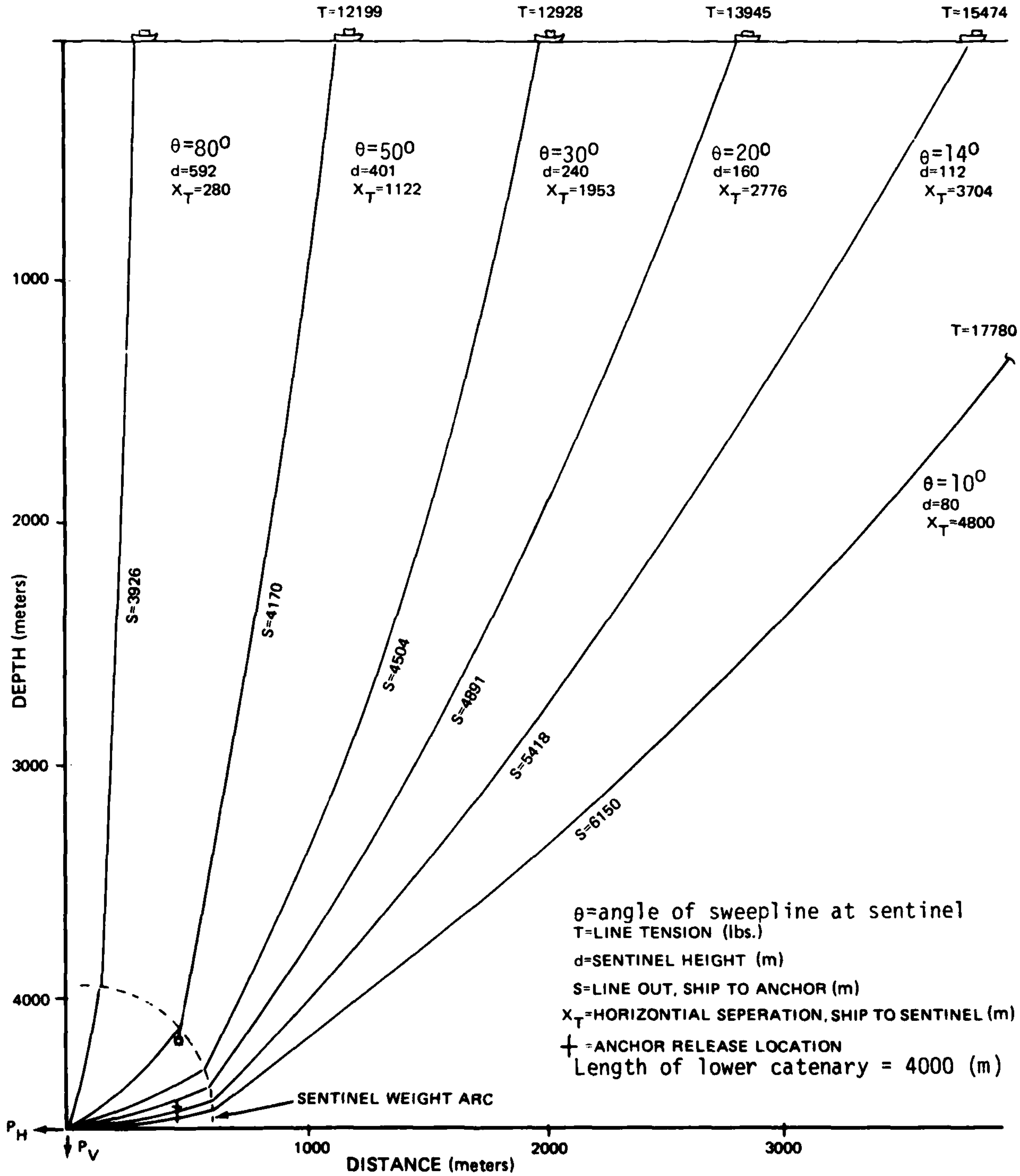

FIGURE 10 CATENARY DETAIL CASE 2

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